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UNITED STATES NONPROVISIONAL APPLICATION

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FOR

IMPROVED GEOMETRY FOR WEB MICROWAVE HEATING OR DRYING
TO A DESIRED PROFILE IN A WAVEGUIDE

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[01] This application claims the benefit of, and incorporates herein by reference, Provisional Application Serial Number 60/228,541 filed August 28, 2000.

[02] This invention was made with Government support under contract no. DE-FC07-00ID13872, awarded by the U.S. Department of Energy. The Government has certain rights in this invention.

Field of the Invention

[03] The present invention relates to a slot design for uniform and prescribed, nonuniform web heating and/or drying in a waveguide. Further, the present invention relates to a slotted waveguide including a field modifier. Further, the present invention relates to a slotted waveguide wherein said field modifier is at least one curvilinear surface which is the narrow wall or which is associated with the narrow wall and which improves heating and/or drying uniformity. Still further, the present invention relates to a slotted waveguide having at least one adjustable surface associated with the narrow walls or at least one adjustable narrow wall and which adjusts heating and/or drying profiles across a paper web.

Background of the Invention

[04] As set forth in Figure 1, a microwave waveguide 10 is generally a system of four walls 30, 40, 50, defining a channel of rectangular cross section along which microwaves propagate. The broad walls 30 are generally perpendicular to the plane of the web 20 and contain a slot 60 through which the web 20 moves. The remaining two walls 40, 50 of the rectangular cross section are the narrow walls. Systems for microwave drying of webs have employed slotted waveguides with the slots along the centerlines of the waveguide broad walls. Typically, the web passes through a linear

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wave is much attenuated, the web is near the lower guide wall 50, where the field amplitude is relatively small. As the wave propagates and attenuates, the height of slot changes to move the web toward the center of the guide. Here, the field is relatively stronger which can allow the maintenance of a more uniform intensity of heat dissipation.

[08] The '275 patent discusses the use of a diagonal slot to roughly compensate for attenuation by moving the web to higher electric field regions away from the source. However, when significant compensation is necessary, as can be the case in the production of paper, a straight diagonal slot is insufficient.

[09] It has not been recognized that a slot height that varies in a non-linear manner with cross-machine position (relative to the narrow wall) can be designed to achieve better heating uniformity. In embodiments according to the present invention, this configuration can allow for complete compensation for the reduction in peak electric field strength due to absorption in the web as the waves propagate across the width of the web.

Summary of the Invention

[010] The present invention provides a microwave waveguide including broad walls separated by, and which are electromagnetically coupled with, at least one field modifier wherein the field modifier has a nonlinear profile.

[011] The present invention further provides a microwave waveguide including at least one adjustable field modifier where the field modifier has a nonlinear profile.

[012] Additional objects and advantages of the invention will be set forth in part in the description which follows, and in part will be obvious from the description, or may

[022] Figure 9 illustrates web heat dissipation relative to the heat dissipation at $z=0$ as a function of waveguide length in meters.

[023] Figure 10 illustrates two configurations for serpentine, slotted waveguide applicator systems according to the present invention.

[024] Figure 11 illustrates the slot location within the waveguide.

[025] Figure 12 plots ideal dimensionless length versus initial slot height.

[026] Figure 13 plots ideal slot shapes at various $h(o)/b$ values.

[027] Figure 14 illustrates efficiency as a function of ideal dimensionless length.

[028] Figure 15 plots efficiency at an ideal length as a function of initial height.

[029] Figure 16 illustrates the normalized drying rate for an ideal slot length.

[030] Figure 17 illustrates the optimal slot profile.

[031] Figure 18 illustrates optimal slot height divided by the waveguide height as a function of distance from the microwave source.

[032] Figure 19 illustrates one waveguide having a curvilinear relative slot height according to the present invention.

[033] Figure 20 illustrates a waveguide having at least one adjustable field modifier.

[034] Figure 21 illustrates a waveguide having actuators for adjusting the at least one field modifier.

Detailed Description

[035] The present invention relates to a slotted waveguide for microwave heating and/or drying of a web that provides improved heating and/or drying uniformity. While the present invention is described in terms of achieving heating or drying

the field modifier, see Figure 21. One or more actuators would be capable of moving the surface of the field modifier, which may be coextensive with the top and/or bottom surfaces of the waveguide, to alter the vertical position of a field modifier surface sufficiently to attain the desired distribution of energy input into the web. In one embodiment according to the present invention, the field modifier is made from a flexible material. In an alternate embodiment, the field modifier is made from one or more rigid, but segmented materials. Any mechanical configuration for adjusting the profile of the field modifier that will allow electromagnetic coupling to be maintained between the field modifier and the broad walls of the waveguide can be used with the present invention. Mechanical configurations other than those described above will be readily apparent to the skilled artisan. Electromagnetic coupling may be maintained using any art recognized method, including, but not limited to physical coupling by, for example, using a conductive grease between the adjustable propagation surface(s) and the broad walls and capacitive coupling.

[041] Both stationary and adjustable microwave waveguides according to the present invention can be used at any point in the web handling process where the use of a microwave heater or dryer is necessary.

[042] It would be readily apparent to the skilled artisan that the desired heating or drying can be achieved based upon modification of the below described calculations. Appropriate heating and/or drying profiles will depend upon the web to be dried and variations in the desired characteristics are readily apparent.

[043] Although the following description is discussed in terms of certain assumptions and equations described herein, the present invention is not limited to

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such assumptions and equations. The assumptions facilitate a concise discussion of the invention. A system consistent with the present invention provides an improved slot profile design for a waveguide for use in uniform web drying. See Figure 3. The symbols used herein for the discussion associated with equations 1-13 are as follows:

List of Symbols

- [044] x coordinate axis along the width (short axis) of the waveguide
- [045] y coordinate axis along the breadth (long axis) of the waveguide
- [046] z coordinate axis along the length of the waveguide
- [047] ϵ_0 permittivity of free space: 8.85×10^{-12} farads/m
- [048] μ permeability of free space: 1.26×10^{-6} henrys/m
- [049] c free space velocity of light: $1/(\epsilon_0\mu)^{1/2} = 2.99 \times 10^8$ m/s
- [050] f frequency of excitation
- [051] ω angular frequency of excitation: $2\pi f$
- [052] a width of waveguide
- [053] b breadth of waveguide
- [054] $h(z)$ the distance between the base of the waveguide and the web slot

as a function of z

- [055] h_0 the initial distance between the base of the waveguide and the web

slot

- [056] H magnetic field
- [057] $E_0(z)$ the center guide amplitude of the E field as a function of z
- [058] E_∞ the center guide amplitude of the E field at $z = 0$
- [059] $D(z)$ the volume intensity of heat dissipation in the web

[060]	f_c	cutoff frequency of TE_{10} mode in waveguide: $c/2b$
[061]	η	impedance of free space: $(\mu/\epsilon_0)^{1/2} = 377 \text{ Ohms}$
[062]	Z	impedance of TE_{10} mode in waveguide: $\eta/(1-f_c/f^2)^{1/2}$
[063]	t	the web thickness in general
[064]	t_d	the designed for web thickness
[065]	t_o	the web thickness in the actual operating waveguide
[066]	ϵ'_r	real part of the dielectric constant of the heated web
[067]	ϵ''_{rd}	minus the imaginary part of the dielectric constant of the web as

[068] ϵ''_{ro} minus the imaginary part of the dielectric constant of the web in operation

[069] ϵ_r dielectric constant of the heated web: $\epsilon_r = \epsilon'_r - i\epsilon''_r$

[070] $\alpha(z)$ amplitude attenuation coefficient

[071] The following assumptions are made for the following discussion associated with equations 1-13.

[072] 1) Either the waveguide is infinitely long or it is terminated with a perfectly matched load. Either way, reflections from the far end of the waveguide (the end opposite the microwave generator) are ignored.

[073] 2) The web thickness is much less than the guide breadth: $t \ll b$.

[074] 3) The propagation characteristics of the wave are determined by free space portions of the guide. The web can be ignored in determining the propagation coefficients.

exiting the differential element is the z-direction component of the surface integral of $E \times H$ over the guide surface at $z+dz$. The energy dissipated in the web is $\omega \epsilon_0 \epsilon'' E^2 \text{atdz}$ integrated over the breadth of the waveguide. In an empty guide running TE_{10} radiation, the integral of the surface integral of propagated power is $E_o^2 ab/2Z$. Since propagation is assumed as in an empty waveguide, the expression at z and $z+dz$ can be used to get net power lost. The field in the web is the same as in the guide; therefore, for the loss term, $E = E_o \sin(\pi h(z)/b)$ is used. A standard energy balance gives:

$$[080] \quad (ab/2Z)(E_o(z)^2 - E_o(z+dz)^2) = \omega \epsilon_0 \epsilon'' E_o^2 \sin^2(\pi h(z)/b) \text{atdz} \quad (1)$$

[081] Expanding E_o in a Taylor series and simplifying gives the attenuation coefficient as a function of excitation, guide, and web properties.

$$[082] \quad \alpha(z) = d(\ln(E_o))/dz = -Z\omega \epsilon_0 \epsilon'' (t/b) \sin^2(\pi h(z)/b)^2. \quad (2)$$

[083] For uniform heating it is necessary to set $h(z)$, so that the dissipation is not dependent on z . This means that $h(z)$ is designed so $dD(z)/dz$ is zero. The only z -dependent terms in $D(z)$ are E_o and h . Thus, the condition for uniform heating is:

$$[084] \quad d/dz (E_o^2 \sin^2(\pi h(z)/b)) = 0$$

$$[085] \quad \text{or}$$

$$[086] \quad d(\ln(E_o))/dz = -(\pi/b) \cot(\pi h(z)/b) dh(z)/dz \quad (3)$$

[087] Substituting from Eqn. (2) for the attenuation coefficient and simplifying makes Eqn. (3) look like this.

$$[088] \quad dh(z)/dz = 2fZ\epsilon_0 \epsilon'' t \sin^3(\pi h(z)/b) / \cos(\pi h(z)/b) \quad (4)$$

[089] Separating variables as a preliminary step to integration yields.

$$[090] \quad dz = [\cos(\pi h(z)/b) / (2fZ\epsilon_0 \epsilon'' t \sin^3(\pi h(z)/b))] dh(z) \quad (5)$$

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[091] Taking the initial boundary condition as $z = 0$ and $h(0) = h_o$ and doing the integration which turns out to be trivial gives:

$$[092] \quad 2fZe_o\epsilon''_rtz = -(b/2\pi)[1/\sin((\pi h(z)/b)^2 - 1/\sin((\pi h_o/b)^2)]. \quad (6)$$

[093] This system compensates only until the slot reaches the center of the guide, or $h(z)$ equals $b/2$. Thus, the range (R) of the compensation is the value of z when $h(z) = b/2$. So, in terms of guide, web, and excitation parameters the maximum web width applicable is

$$[094] \quad R = (b/2\omega Ze_o\epsilon''_rt)[1/\sin((\pi h_o/b)^2 - 1)] \quad (7)$$

[095] So, for a given guide and driving frequency, the range is a function ϵ''_rt and h_o/b . Now, Eqn. (6) for the ideal slot shape function, $h(z)$, is solved. The answer is:

$$[096] \quad \pi h(z)/b = \arcsin[(1/\sin((\pi h_o/b)^2 - 2\omega Ze_o\epsilon''_rtz/b)^{-1/2}] \quad (8)$$

[097] The next step is to integrate Eqn. (2) to get the E field as a function of z . Before doing this, the notation is extended. In estimating the robustness, for heating and drying of the ideal slot shape function, the web is evaluated in a guide designed for other webs. So, from now on, ϵ''_{rd} and t_d are used to represent the parameters for web in design and ϵ''_{ro} and t_o to represent the parameters for web in operation. So, the differential equation for E_o in an operating guide is

$$[098] \quad d(\ln(E_o))/dz = -Z\omega e_o\epsilon''_{ro}(t_o/b)\sin((\pi h(z)/b)^2) \quad (9)$$

[099] where $h(z)$ comes from the design parameters, i.e.

$$[0100] \quad \pi h(z)/b = \arcsin[(1/\sin((\pi h_o/b)^2 - 2\omega Ze_o\epsilon''_{rd}t_dz/b)^{-1/2}] \quad (10)$$

[0101] Now inserting Eqn. (10) into Eqn. (9) gives

$$[0102] \quad d(\ln(E_o))/dz = -Z\omega e_o\epsilon''_{ro}(t_o/b)[1/\sin((\pi h_o(z)/b)^2 - 2\omega Ze_o\epsilon''_{rd}t_dz/b)]^{-1} \quad (11)$$

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[illegible]

$$[0104] \quad E_o^2/E_{oo}^2 = [1 - \sin((\pi h_o(z)/b)^2 2\omega Z e_o \epsilon''_{rd} t_o z/b)]^{\epsilon''_{roto}/\epsilon''_{rd} t_d} \quad (12)$$

[0105] Now, the dissipation in the operating guide as normalized to the dissipation in the designed guide at $z = 0$, $D_o(z)/D_d(0)$, is:

$$\begin{aligned}
[0106] \quad D_r(z) &= (\epsilon''_{ro}/\epsilon''_{rd}) (E_o^2/E_{oo}^2) [(\sin(\pi h z/b)^2/\sin(\pi h_o/b)^2)] \\
[0107] \quad &= (\epsilon''_{ro}/\epsilon''_{rd}) [1 - \sin(\pi h_o/b)^2 2\omega \epsilon_o \epsilon''_{rd} z/b] \epsilon''_{ro}/\epsilon''_{rd} t^{-1} \quad (13)
\end{aligned}$$

Numerical Examples

[0108] A comparison of straight slot compensation to Eqn (8) curved slot compensation is made in Figure 5. For maximum drying intensity, the slot should end at the mid-plane ($h = b/2$). Figure 5 presents the dissipation profiles for straight slot compensations that force the drying rates to be equal at the beginning and end of the waveguide where $h = b/2$. The degree of compensation increases and h_0 approaches zero. When there is little absorption across the waveguide and h_0 can be nearly $b/2$, the linear slot solution is adequate. However in the more practical applications requiring high drying rates and low initial slot heights the straight slot performs poorly. In contrast, the Eqn. (8) curved slot gives substantially complete or complete compensation for all cases.

[0109] The following demonstrates the range of compensation for drying paper webs is sufficient. With practical waveguide design parameters, the compensation should extend the width of a typical paper machine (about 10m). In Figure 6, the range of compensation is graphed as a function of h_0/b for webs of different ϵ''/t . The system

discussed operates in an S-Band waveguide at 2.45 GHz and allows $\epsilon''t$ to vary over a reasonable range corresponding to thin, dry papers to thick, heavy papers.

[0110] Figure 7 presents a slot curve. From inspection of Eqns. (7) and (8), it can be concluded that this curve is independent of $\epsilon''t$ if $h(z)$ is plotted with z normalized to the range of compensation. So, Figure 7 can be considered a universal curve for S-Band 2.45 GHz operation.

[0111] Figure 8 presents centerline field intensity for the perfectly compensated case as a function of guide length plotted for $\epsilon''t = 10^{-4}$ in an S-Band guide at 2.45 GHz. Figure 9 gives the power dissipation intensity as a function of z for the designed web and for webs with $\epsilon''t$ different from the expected. Notice that the percentage of cross web variability is roughly equal to the percentage deviation of $\epsilon''t$ from the designed value.

[0112] Two configurations for serpentine, slotted waveguide applicator systems are depicted in Figure 10. Type (a) has a reflector (short) at the termination end, and a circulator and load at the supply end, while type (b) has a dummy load at the termination end. In type (a), energy not absorbed in the web after travel from the source to the short will be reflected, and have the opportunity to be partially absorbed before it reaches the load. This design will have a standing wave along the applicator, making it challenging to achieve uniform heating of the web. Type (b) is discussed further herein and will (ideally) have no reflections and no standing wave pattern. Note that a special case of each of the serpentine systems in Figure 1 would be a corresponding single-pass version. In the analysis to follow, the single-pass system will be the initial focus, but the results will then be extended to the multi-pass configuration.

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machine speeds, the results derived here should serve as a suitable 'building block.'

The analysis may be extended to the design of applicators with a reflector (short) or other specified termination, instead of a load at the end opposite the power source.

The following notation conventions are for equations 14-38.

NOTATIONS FOR EQUATIONS 14-38

a	narrow dimension of waveguide cross-section	m
b	broad dimension of waveguide cross-section	m
BW	paper (dry) basis weight	g/m ²
D _v	volumetric dissipation rate in moist paper	W/m ³
D'	dissipation rate per unit distance along guide	W/m
E	electric field	V/m
f, f ₀	microwave frequency, cutoff frequency	GHz
h	elevation of slot above bottom of waveguide	m
L	active length of waveguide	m
L ₀	absorption length (equation 11)	m
\dot{m}_D''	drying rate	kg/(m ² -s)
m _r	moisture ratio	g water/g solid
m_w''	water loading	g/m ²
N	number of passes	-
P	electromagnetic power	W
t	paper thickness	m
y	distance above bottom of waveguide	m
z	distance along waveguide	m
Z	waveguide impedance = $377/[1 - (f_0/f)]^{1/2}$	ohm

Greek

$\bar{\alpha}$	mean absorption coefficient (equation 10)	1/m
ϵ_0	permittivity of free space (8.85×10^{-12})	farads/m
ϵ_r''	dielectric loss coefficient	-
λ	latent heat of vaporization	kJ/kg
η	efficiency	-
ω	angular frequency	1/s
$\Delta \bar{h}$	change in normalized slot height = $1/2 - \bar{h}(0)$	m

<i>Subscripts</i>		<i>Subscripts</i>	
ideal	ideal slot height variation case	PM	paper machine
in	waveguide inlet (power input end)	Ref	reference value
linear	linear slot height variation case	1-pass	one (first) pass
max	maximum, at a given cross-section	water	water only
out	waveguide exit (load end)		
overall	for all N passes	<i>over bar</i>	dimensionless
p	paper		quantities, defined in
			text by equations
			25, 26, 27, 35

[0116] Principles and Approximations - The approximation of an ideal system in which the only loss of electromagnetic power is that due to dissipation in the wet paper (i.e., no dissipation in the waveguide walls or leakage out the slot) seems reasonable.

The rate of dissipation per unit volume of web is given by:

$$[0117] \quad D_v = \omega \epsilon_0 \epsilon_r'' E_p^2(z) \quad (14)$$

[0118] where $E_p(z)$ is the electric field at the location of the web and slot, $h(z)$ (see Figure 11). Multiplying by the web cross-sectional area (at) (dimensions defined in Figure 11) yields the total rate of dissipation per unit z -directional distance:

$$[0119] \quad D'(z) \equiv at D_v(z) = at \omega t_0 \epsilon_r'' E_p^2(z) \quad (15)$$

[0120] At the waveguide cross-section located at any z , the total electromagnetic power propagating into that cross-section is $P(z)$. The law of conservation of energy is:

$$[0121] \quad \frac{dP(z)}{dz} = -D'(z) \quad (16)$$

[0122] Since paper is a very thin material compared to the waveguide height (b), a good approximation for the E -field distribution at a waveguide cross-section at any z is:

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$$[0123] \quad E(y,z) = E_{\max}(z) \sin\left(\frac{\pi y}{b}\right) \quad (17)$$

[0124] $E_{\max}(z)$ is the amplitude and occurs at the mid-plane ($y = b/2$). If the thin wet web is located at the elevation:

$$[0125] \quad y = h(z) \quad (18)$$

[0126] it would thus experience an E-field:

$$[0127] \quad E_p(z) = E_{\max}(z) \sin\left(\frac{\pi h(z)}{b}\right) \quad (19)$$

[0128] Because of the sinusoidal variation in E, the total electromagnetic power propagating in the z-direction inside the waveguide at the cross-section located at any z is adequately approximated by:

$$[0129] \quad P(z) = \frac{ab}{2Z} E_{\max}^2(z) \quad (20)$$

[0130] where Z is the waveguide impedance (not dependent on the wet web properties).

[0131] No additional principles are needed in order to examine how well various candidate paper elevation profiles $[h(z)]$ can experience a degree of uniformity of heating (i.e., of dissipation of electromagnetic power). Of course, the elevation profile shapes that would provide complete uniformity can be determined.

[0132] To facilitate the analysis, equations 15, 16, 19 and 20 can be combined to achieve a differential equation that describes the variation of E-field experienced by the paper with position, z:

$$[0133] \quad \frac{d}{dz} \left(\frac{E_p^2(z)}{\sin^2\left(\frac{\pi h(z)}{b}\right)} \right) = -\frac{2tZ\omega t_0 \epsilon_r''}{b} E_p^2(z) \quad (21)$$

[0134] The general solution of equation 21 is:

$$[0135] \quad E_p(z) = \left(\frac{\sin\left(\frac{\pi h(z)}{b}\right)}{\sin\left(\frac{\pi h(0)}{b}\right)} \right) E_p(0) e^{-\bar{\alpha}z} \quad (22)$$

$$[0136] \text{ where: } \bar{\alpha}z = \int_0^z \left(\frac{tZ\omega Z_0 \epsilon_r''}{b} \right) \sin^2\left(\frac{\pi h(z)}{b}\right) dz \quad (23)$$

$h(0)$ = paper elevation at the inlet ($z=0$)

[0137] $E_p(0)$ = E-field at the inlet, at $y=h(0)$, calculable from the input power $P_{in}=P(0)$, using equations (19) and (20).

[0138] It is useful to recognize the grouping of parameters:

$$[0139] \quad L_0 \equiv b/(Z\omega t_0 \epsilon_r'') \quad (24)$$

[0140] as representing a meaningful length scale for absorption of microwave energy by the moist web. Normalizing the waveguide (single-pass) length by this quantity defines a dimensionless waveguide length parameter:

$$[0141] \quad \bar{L} \equiv L/L_0 \quad (25)$$

[0142] Intuitively, a large \bar{L} would correspond to a length over which the moist web absorbs much of the input energy. A dimensionless position can be introduced along the waveguide as:

$$[0143] \quad \bar{z} = z/L \quad (26)$$

[0144] Furthermore, the slot (and web) location can be normalized by height b :

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[0145] $\bar{h}(\bar{z}) = h(\bar{z})/b$ (27)

[0146] Using equations (25-27), equation (23) can be rewritten:

[0147] $\bar{\alpha}z = \int \bar{L} \sin^2(\pi \bar{h}(\bar{z})) d\bar{z}$ (28)

[0148] It can be noticed that, for the special case of $h(z) = \text{constant}$:

[0149] $E_p(\bar{z}) = E_p(0)e^{-\bar{\alpha}z}$ (29)

[0150] In this case, $\bar{\alpha}$ is constant (but dependent on the value selected for $h(0)$, due to the \sin^2 term in equation 28). However, in the general case, $h(z)$ not constant, $\bar{\alpha}$ varies with z , and there is also a variable factor before the exponential term in equation 22.

[0151] It is of interest to know the slot design $[h(z)]$ that provides uniform heating of the web across the width of the web machine. This corresponds to the special case of $E_p(z) = \text{constant}$. The solution of equation 21 (in dimensionless variables) is then:

[0152]
$$\bar{h}(\bar{z}) \equiv h(\bar{z})/b = \frac{1}{\pi} \sin^{-1} \left\{ \left[\frac{1}{\sin^2(\frac{\pi h(0)}{b})} - 2\bar{L}\bar{z} \right]^{\frac{1}{2}} \right\}$$
 (30)

[0153] It is useful to recognize that, for a given initial slot height $(\bar{h}(0))$, there is a maximum value of \bar{L} that can be used for uniform heating via the variable slot height technique. This value corresponds to $\bar{h}(\bar{z}=1) = 0.5$, signifying that the slot ends at the mid-plane of the waveguide. This "ideal dimensionless length" is, from equation (30):

$$[0154] \quad \bar{L}_{\text{ideal}} = \frac{1}{2} \left(\frac{1}{\sin^2(\pi h(0))} - 1 \right) \quad (31)$$

[0155] The variation of ideal length with initial slot height is shown in Figure 12.

[0156] Example slot shapes, computed by inserting the ideal length values into equation (30), are shown in Figure 13. Note that slots starting farther from the midplane have much more curvature near the outlet end of the waveguide. They also provide more complete absorption of the input power by the web. The completeness of absorption can be measured by an efficiency, defined as:

$$[0157] \quad \eta = (P_{\text{in}} - P_{\text{out}}) / P_{\text{in}} \quad (32)$$

[0158] For ideal slots (uniform absorption and termination at the mid-plane), it can be shown that :

$$[0159] \quad \eta = 2\bar{L}_{\text{ideal}} / (1 + 2\bar{L}_{\text{ideal}}) \quad (33)$$

[0160] This relation, and an alternate one in terms of $\bar{h}(0)$ (via equation (31)), are shown in Figures 14 and 15.

[0161] While efficiency is important, so, too, is drying rate (per unit area). With a view toward use of multi-pass (serpentine) applicator units, the machine-direction (MD) length (per pass) can be (arbitrarily) defined as (a / f_{WG}) , which includes both the open (non-waveguide) area between passes and the waveguide MD width. A reference drying rate, based on the absorption length and on the approximation that all energy absorbed produces evaporation, can then be defined as:

$$[0162] \quad \dot{m}''_{\text{D,Ref}} \equiv f_{\text{WG}} P_{\text{in}} / (\lambda(\lambda_0)) \quad (34)$$

[0163] The actual (dimensionless) drying rate for an ideal-length waveguide can be shown to be:

$$[0164] \quad \bar{m}_D'' = \dot{m}_D'' / \dot{m}_{D,Ref}'' = \left(\frac{2}{1+2L} \right) = 2(1-\eta) \quad (35)$$

[0165] This relationship is shown in Figure 14. Considering Figures 15 and 16 together, there is a tradeoff between efficiency (operating cost) and drying intensity (space and capital cost).

EXTENSION OF IDEAL SLOT RESULTS TO SERPENTINE (MULTI-PASS) APPLICATORS

[0166] For paper manufacture applications, the ranges of basis weight and moisture content of interest, together with the selected frequency (0.915 GHz or 2.45GHz), will correspond to a wide range of L_0 values. In combination with the range of typical paper machine widths (L_{PM}), a wide range of \bar{L}_{ideal} is, thus, to be expected. From the results presented, it can be seen that there are some paper manufacture applications for which a single-pass applicator would have an unacceptably low efficiency. In this situation, additional passes to absorb energy not absorbed in the first pass, would be indicated.

[0167] Two alternative multi-pass system design strategies can be considered. One strategy (#1) would be to select the same "initial slot height" for each pass, ending the slot at the mid-plane for each pass. The other (#2) would be to consider the total active length of the multi-pass system to be equivalent to one longer pass, with the slot shape varying continuously over the entire unit (reaching the mid-plane only at the end of the final pass). For these strategies, the initial slot height for (#1) would clearly have

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to exceed that for (#2), assuming L_0 is constant. It appears that strategy (#1) will always yield higher efficiency than strategy (#2), for a given number of passes.

[0168] For strategy (#1), with N passes, the following results are easily derived:

$$[0169] \quad \eta_{\text{overall}} = 1 - (1 - \eta_{1\text{-pass}})^N \quad (36)$$

[0170] and, (using equation 35 to get the second form):

$$[0171] \quad \bar{m}_{D,\text{overall}}'' = \bar{m}_{D,1\text{-pass}}'' \left[\frac{\sum_{i=1}^N (1 - \eta_{1\text{-pass}})^{i-1}}{N} \right] = 2 \left[\frac{\sum_{i=1}^N (1 - \eta_{1\text{-pass}})^i}{N} \right] \quad (37)$$

[0172] Thus, the efficiency of a multi-pass system increases, but the average drying rate decreases, compared to those for a 1-pass system.

[0173] In applying the above results, parameters are specified for the waveguide (frequency, dimensions, and impedance), the moist paper (dielectric loss coefficient), and the paper machine (cross-direction length and water loadings). Approximate values for water are utilized, together with data for moist paper at another frequency, to make a preliminary estimate (via a procedure outlined below) of the required loss coefficients.

The waveguide parameters and water loss coefficient values are given in Table 1. The wide ranges of water loadings (the product of paper basis weight and moisture ratio) and cross-direction lengths (LPM) of potential interest for the paper industry (encompassing applications from web heating through the drying process) are given in

Table 2.

Table 1. Waveguide and Water Loss Coefficient Parameters.

f(GHz) frequency	f _c (GHz) [cutoff frequency]	Z (ohm)	a(m)	b(m)	ε _r '' , water at 25 °C	ε _r '' , water at 50 °C
0.915	0.605	503	0.124	0.2477	3.5	1.8
2.45	2.078	712	0.034	0.0721	9	5

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Table 2. Typical Paper Manufacture Parameter Ranges.

	BW, g/m ²	m _r , kgwater/kgsolid	m _w ["] , g/m ²	L _{PM} , m
I. Min (approx.)	15	0.1	1.5	1 (pilot PM)
Max (approx.)	300	2	600	10

[0174] The analysis in the preceding section has shown that it is actually the product $\epsilon''_r t$ that is important in characterizing applicator performance. The available data on loss coefficient for moist paper indicate that, above moisture contents of about 12%, the loss coefficient is approximately directly proportional to the apparent density of water in the structure (i.e., the mass of water per unit volume of paper). Therefore, multiplying both the loss coefficient and the apparent water density by the thickness (t) we see that $\epsilon''_r t$ is a function of water loading (mw", g/m2), for a given frequency and temperature. The cited data also indicate that, at water apparent densities approaching unity, the loss coefficient is only about half that for pure water. Extrapolating the above observations to the case of other frequencies and temperatures, an approximate relationship for $\epsilon''_r t$ is found:

$$[0175] \quad \epsilon''_r t \approx 0.5 \times 10^{-6} \epsilon''_{r, \text{water}} m_w'' \quad (38)$$

[0176] if t is in meters and m_w'' in g/ m2.

[0177] With the approximate relationship described by equation 38, data from Tables 1 and 2 can be employed to calculate the values of the absorption length for frequencies and water loadings of interest. The results of such calculations are given in Table 3.

[0178] There are some soft constraints on the range of waveguide designs that are of practical interest. First, there must be a lower bound on the initial height ratio,

$h(0)/b$, because it would be difficult to ensure that the paper could travel very close to the bottom wall of the waveguide. A suggested lower bound for this ratio would be about 0.1. According to equation 31, this would constrain the ideal dimensionless length to

$$\bar{L}_{ideal} \leq 4.74$$

[0179] A second constraint would be related to the desire that the single-pass efficiency not be too low, because otherwise the number of passes need to get good overall efficiency would become large (see equation 37), causing the average drying rate to become small (see equation 38). For example, if the number of passes were limited to five, a single-pass efficiency of at least about 30% would be needed to achieve an overall efficiency above 80%. Using a single-pass efficiency of 30% as a suggested bound, the corresponding bound on ideal dimensionless length would be (approximately): $\bar{L}_{ideal} \geq 0.21$.

Table 3. Estimated Absorption Length (L0) Values.

f (GHz)	m_w'' (g/m ²)	Temperature (°C)	$\epsilon''t$ (m)	L0 (m)
0.915	1.5	25	0.000002625	3687.09
0.915	30	25	0.0000525	184.35
0.915	600	25	0.00105	9.21
0.915	1.5	50	0.00000135	7169.36
0.915	30	50	0.000027	358.46
0.915	600	50	0.00054	17.92
2.45	1.5	25	0.00000675	110.11
2.45	30	25	0.000135	5.50
2.45	600	25	0.0027	0.27
2.45	1.5	50	0.00000375	198.21
2.45	30	25	0.000075	9.91
2.45	600	50	0.0015	0.49

[0180] If an example paper machine width of 5m is considered, the definition of dimensionless length (equation 25) with the upper and lower bounds just identified can be combined, to establish a corresponding range of absorption length values:

$1.06m \leq L_0 \leq 23.7m$. This range should correspond to the most promising papermaking

[illegible][illegible]